Analysis of Critical Success Factors for Implementing Industry 4.0 Integrated Circular Supply Chain – Moving towards Sustainable Operations

Abstract

Many threats, such as scarcity of sources and climate change, are forcing the business community to examine their commitment towards the environment and society. Because of this pressure, companies have started to implement long term sustainable practices into their operations. An example of this is the adoption of circular supply chain (CSC), Industry 4.0. How the integration of Industry 4.0 and CSC can be implemented to achieve sustainable supply chain operations is an important question for research. Very little discussion is available in current literature in this regard. This study objective is to analyse the critical success factors (CSFs) for this integration. A three-phase study framework has been utilized to achieve the objective. In the first phase, CSFs are identified through literature review and experts' inputs; in the second phase, an empirical research is conducted for finalization of CSFs and in the last phase, influencing and influenced factors are identified by using Hesitant based Fuzzy DEMATEL. The analysis shows that in the adoption of CSC integrated with Industry 4.0 to achieve sustainability in supply chain operations, 'knowledge of CSC and Industry 4.0' is the most important factor followed by 'top management commitment'. With the help of this research study's findings, both theoretical and practical contributions are provided which further help the operation. This will assist supply chain managers in achieving sustainability in supply chain operations through an effective adoption of the integration of CSC and Industry 4.0.

Keywords: Circular supply chain, Industry 4.0, Critical Success Factors, Hesitant Fuzzy DEMATEL, Sustainability, Operation excellence

1. Introduction

The largest 2500 global firms contribute more than 20% of greenhouse gas emissions throughout the world; moreover, their supply chains are accountable for a large proportion of emissions produced by their corporate operations (Dubey et al., 2017). Worries relating to climate change and critical raw material scarcity have grown at global level (Boons et al., 2013). Growing industrialization is resulting in increasing resource consumption, growing energy needs, global warming and intensifying climate change problems (Kamble et al., 2018b). These trends will possibly intensify further as demand for goods and services are expected to grow rapidly due to an addition of approximately three billion consumers worldwide by 2030. The usual business approach of taking, manufacturing, using and disposing of goods is an inadequate model for manufacturers for sustainability purposes (Williams, 2001). Therefore, it is very important to transform the entire supply chain (Low et al., 2016). A circular supply chain (CSC) embodies a restorative system of manufacturing where resources are put into an infinite circle (Sharma et al., 2019). The CSC management fits into a circular economy (CE) which attempts to enhance resource deployment all through the life cycle of the product via re-manufacturing, recycling etc. (Genovese et al., 2017; Sharma et al., 2019). Also, CE is supportive in dealing with the issue of ecological deterioration and resource scarceness in the business context (Geng et al. 2009; Mangla et al., 2018a). CE synchronizes economic growth, environmental protection and social benefits; it offers superior value creation at organizational level by managing waste, extending product life cycle and developing low-cost sustainability via banking upon customer preferences for secondary products (Mangla et al., 2018a). Therefore, CSC offers ways to address issues such as pollution, climate change and resources scarcity via waste reduction and minimization of the harmful impact of supply chain practices (Genovese et al., 2017; Nasir et al., 2017). Although some organizations are systematically moving towards building circular supply chain models (Mangla et al., 2018a), there are various hurdles in its adoption, especially in the context of emerging economies like India (Goyal et al., 2016; Yaduvanshi et al., 2016). These include lack of technological advancements (Mangla et al., 2018a).

Jabbour et al. (2018b) have argued that Industry 4.0 technologies acceptance is moving towards circular economy principles. Technologies such as internet of thing (IoT), cloud computing, big data analytics etc. can provide various ways to track products post-consumption so that components can be recovered. The term "Industry 4.0" originated in Germany (Drath and Horch, 2014) and symbolizes a new and influential wave of industrialization (Jabbour et al., 2018b) which enables smart manufacturing. Industry 4.0 also helps decision makers to safeguard the environment via resources efficiency and incorporating flexible and smarter processes in the supply chain; the aim is to make available information about machines, production and flow of components on a real time basis and integrate this information to assist decision makers in monitoring the performance while tracking parts and products. (Lu, 2017; Mangla et al., 2018b; Jabbour et al., 2018b). Industry 4.0 is expected to bring in disruptive transformation in supply chains, business processes and business models (Schmidt et al., 2015; Tjahjono et al., 2017; Kamble et al., 2018b).

We argue that CSC is an integral component of a circular economy and is an effective way of moving towards sustainability by creating a sustainable supply chain. Additionally, Industry 4.0 not only facilitates adoption of CSC, but also contributes towards organizational sustainability in multiple ways. Therefore, the adoption of CSC and Industry 4.0 in an organization goes hand in hand and can be complementary to each other. In an emerging economy context, Mangla et al. (2018a) and Sharma et al. (2019) have explored implementation of CSC. Luthra and Mangla (2018) have investigated the challenges of Industry 4.0 for achieving sustainability. However, after reviewing existing literature, we came to realize that there is no study which looks into the critical success factors at organizational level regarding the successful integration of CSC and Industry 4.0 to augment its environmental, economic and social sustainability. Thus, the research questions which are following the objectives of this study are:

RQ1: What are the critical success factors (CSFs) in the purview of an organisation that are crucial for building requisite capabilities for implementation of Industry 4.0 integrated CSC *to boost sustainability in its supply chain operations?*

RQ2: What are the cause-effect associations among the considered CSFs and how can these relationships be analysed in order to guide practitioners and decision makers to formulate more meaningful plans and strategies?

RQ3: Guided by the study findings, which are the key practical implications and strategies that may support practitioners and decision makers to achieve the adoption of Industry 4.0 integrated CSC*?*

The following section 2 presents a literature review aimed at identifying the CSFs in the set context. Section 3 details the methodology used for analysis. Section 4 presents information about how the methodology framework is applied to carry out the research and also envelops the research output. Section 5 covers the theoretical and managerial implications along with future research directions. The last section presents concluding remarks on the current work.

2. Literature review

2.1. Industry 4.0 integrated CSC and sustainable supply chain operations

Due to a depleting ozone layer, global warming and environment degradation, the issue of creating sustainable SC has received much attention in recent years (Büyüközkan and Çifçi 2011). By putting material, products and wastes into a circular flow, organisations are attempting to address the issue of harmful effects of their supply chain activities (Nasir et al. 2017). In this way, CSC has emerged as a tool to bring sustainability to supply chain operations by tackling critical issues like pollution, unsustainable patterns of production, consumption and resource scarcity (Mangla et al., 2018). Recently conducted studies (Jabbour et al., 2017a, 2017b) have identified Industry 4.0 as a key contributor towards implementing principles of a circular economy. From an emerging economy perspective, Batista et al. (2018) discussed CSC issues related to packaging recovery ecosystems in two emerging economies i.e. China and Brazil. Bressanelli et al. (2018) carried out a complete literature review about the challenges in SC redesign for the CE; in the same year, the transition challenges of SCM to CSC have been discussed by De Angelis et al (2018). Sharma et al. (2019) explained the challenges in adoption of CSC practices in a food supply chain. But these studies did not say anything about the critical success factors for implementing Industry 4.0 Integrated CSC to further help the business community to move towards sustainable operations. India, as the fastest growing economy in the world, is witnessing economic activities develop extremely quickly; the country requires this growth to become a fully developed nation (Mangla et al., 2018; Sharma et al., 2019). Hence, sustainable development becomes more crucial in the Indian context. Consequently, implementing CSC integrated with Industry 4.0 would help companies to ensure sustainability in their operations. Keeping this in mind, it is important to understand CSFs in this regard. The following section details the CSFs to ensure the successful adoption of Industry 4.0 integrated CSC.

2.2. Critical success factors at organisational level

CSFs at an organisational level were drawn from the current literature and validated through inputs from experts. Hence, in the first phase, a systematic literature review (Luthra et al., 2018; Yadav et al., 2018a) was carried out by using certain key words such as: critical factors, success factors, enablers, motivators, circular economy, circular supply chain, remanufacturing, organisational success factor, drivers of Industry 4.0 and circular supply chain, sustainability in supply chain management etc. leading to identification of 14 CSFs. In the second stage, these 14 CSFs were validated in their applicability in the set context via experts' inputs as further described in section

4. Table 1 itemises these fourteen CSFs along with their literature sources; the sub-section below explains each of them.

Table 1. CSFs for implementing Industry 4.0 integrated CSC

CSFs	References
Coordination and collaboration among supply chain partners	Fischer and Pascucci, 2017; De Angelis et al., 2018; Luthra and Mangla, 2018; Mangla et al., 2018a
Change management	Jones et al., 2005; Shamim et al., 2017; Jabbour et al., 2018b; Luthra and Mangla, 2018
Knowledge of circular supply chain and Industry 4.0	Benton et al., 2015; Khan and Turowski, 2016; Basl, 2017; Mangla et al., 2018a
Training and development programs	Sarkis et al., 2010; Jabbour and Jabbour, 2016; Waibel et al., 2017; Jabbour et al., 2018b; Luthra and Mangla, 2018; Mangla et al., 2018a
High quality data	Jabbour et al., 2018b; Luthra and Mangla, 2018
Effective planning and execution	Mangla et al., 2018a
Integration of technology platforms	Zhou et al., 2015
Data security	Ngai et al., 2004; Sommer, 2015; Pereira, 2017; Luthra and Mangla, 2018;
Knowledge management system	Chen and Huang, 2009; Tatham and Spens, 2011; Shamim et al., 2016; Luthra and Mangla, 2018
Ability to adopt new business models	Saucedo-Martínez et al., 2017; Khan et al., 2017; Luthra and Mangla, 2018; Mangla et al., 2018a
Skilled and semi-skilled employees	Zhu and Geng, 2013; Jabbour et al., 2018b
Top management commitment	Young and Jordan, 2008; Dong et al., 2009; Giunipero et al., 2012; Venkatesh and Luthra, 2016; Zhu and Geng, 2013 Jabbour et al, 2018b; Luthra et al., 2018
Management leadership	Shao et al., 2017; Jabbour et al., 2018; Onar et al., 2018
Financial resources	Theorin et al. 2017; Luthra and Mangla, 2018

2.1 Coordination and Collaboration among SC Partners

Mangla et al. (2018a) and De Angelis et al. (2018) indicated that to transform the SC in India to integrate the circular flow of material and information to promote remanufacturing, reuse and recycle, organisations need to build strong coordination and collaboration among supply chain partners. Organizations must ensure collaboration among various stakeholder for the application of circular economy principles and Industry 4.0 (Fischer and Pascucci, 2017). Additionally, various studies elaborate the significance of coordination and collaboration for integrating Industry 4.0 with SC to augment sustainability in SC operations (Pfohl et al., 2017; Luthra and Mangla, 2018).

2.2 Change Management

The adoption of CSC supported by Industry 4.0 will result in multiple changes in an organization at various levels; there will be a demand for new labour skills throughout the company. Change management can be assumed as omnipresent for an organization (Todnem, 2005); this involves re-drafting organizational structure, strategy and objectives in response to change on a continuous basis (Moran and Brightman, 2001). Therefore, an organization's ability to manage change evolving from Industry 4.0 and CSC implementation is likely to play a decisive role in its success (Jabbour et al., 2018b; Shamim et al., 2017).

2.3 Knowledge of Circular Supply Chain and Industry 4.0.

Implementing CSC and Industry 4.0 requires knowledge and awareness of these concepts among various stakeholders such as customers, employees, suppliers etc. Lack of such awareness and knowledge restricts the organizational ability to implement CSC through introducing superior products and systems to encourage repair, re-manufacture, recycle etc. (Benton et al., 2015; Mangla et al., 2018a). Additionally, low awareness of Industry 4.0 adversely influences an organization's ability to adopt Industry 4.0 (Khan and Turowski, 2016; Basl, 2017). Therefore, we argue that for an integrated application, organizations need to raise awareness and knowledge regarding CSC and Industry 4.0 among its stakeholders.

2.4 Training and Development Programs

Having skilled and semi-skilled employees is critical for organisations to implement Industry 4.0 integrated CSC successfully. Consequently, organisations should hire employees who are equipped with the necessary skills and who are receptive to training and development programs to upgrade and develop their skills even further (Yadav et al., 2018c). The provision of training and development programs by an organisation contributes to its ability to successfully implement CSC integrated with Industry 4.0 by diffusing requisite skills to its employees and supply chain members (Jabbour and Jabbour, 2016; Jabbour et al., 2018b; Luthra and Mangla, 2018).

2.5 High Quality Data

Various machines, systems and facilities are inter-connected in Industry 4.0 to generate big data; this is then used to enable decision makers to boost organizational sustainability in multiple ways. Therefore, data quality is critical for efficient decision making. Data quality is considered as a key challenge for sustainable SC and Industry 4.0 (Jabbour et al., 2018b; Luthra and Mangla, 2018).

Integrating supply chain with Industry 4.0 depends upon accuracy of data (Asif, 2005). For instance, accuracy of readers is observed to be below 90% (Rothfeder, 2004). Asif (2005) indicated various reasons why RFID does not generate accurate data, meaning likely interruptions in CSC. Hence, organizations are expected to ensure high quality data for integrating Industry 4.0 with CSC operations.

2.6 Effective Planning and Execution

Effective planning and execution play an important role in the attainment of desired objectives. Adopting Industry 4.0 integrated CSC also requires proper planning as well as execution of these plans in order to put resources into an infinite loop of reuse, re-manufacture and recycle. Efficient planning and execution provide clarity to stakeholders about their roles and responsibilities (Yadav et al., 2018b). However, any loophole in the planning process and compromise in the implementation of charted plans may result in failure to achieve the implementation of circular supply chain integrated with Industry 4.0 (Mangla et al., 2018a).

2.7 Integration of Technology Platforms

A combined implementation of circular supply chain and Industry 4.0 is important as both are likely to be complementary to each other. It should be noted that both mentioned strategies are technological intensive and require efficient communication (Yadav et al., 2017; Kamble et al., 2018c). Luthra and Mangla (2018) specify that integration of various technology platforms is vital for enhancing sustainability in supply chain through Industry 4.0. Therefore, we consider the organizational ability to integrate its technology platforms as a key factor in the stated context.

2.8 Data Security

Industry 4.0 not only generates data but also utilises it to enhance organisational efficiency (Jabbour et al., 2018b). Data security has been raised as a major challenge for implementing Industry 4.0 and therefore, protecting data is of key importance for organisations (Sommer, 2015). Industry 4.0 techniques are critical for the recovery of products post consumption (Jabbour et al., 2018a); other researchers have also commented on their importance for CSC (Ngai et al., 2004). Luthra and Mangla (2018) also specify data security as crucial for boosting the usage of Industry 4.0 for achieving sustainability in SC. Therefore, an organisation which has systems to ensure data security in place is likely to achieve integrated adoption of Industry 4.0 and CSC successfully.

2.9 Knowledge Management System

Knowledge supports organizations to attain a competitive edge in a dynamic environment (Spender and Grant, 1996; Lin, 2007). Knowledge management systems are crucial for enhancing organizational performance (Tatham and Spens, 2011; Hu and Randel, 2014) and contributes towards developing human resources of an organization in various ways (Tatham and Spens, 2011). To ensure adoption of Industry 4.0 integrated CSC, firms call for innovations. The capability of employees to innovate is an outcome of learning and knowledge (Shamim et al., 2016). In other words, knowledge management boosts employee creativity and ability to innovate (Chen and Huang, 2009). Therefore, having an efficient knowledge management system that facilitates knowledge creation and knowledge exchange in place within an organization is a key to boosting supply chain sustainability by integrating a circular approach in SC and Industry 4.0.

2.10 Ability to Adopt New Business Models

A circular supply chain aims to address issues related to depleting resources and a deteriorating environment via reuse, re-manufacturing, recycling etc.; Industry 4.0 initiatives can transform the methods through which products are designed, manufactured, delivered and disposed of by companies (Luthra and Mangla, 2018). To adopt a philosophy of circular economy integrated with Industry 4.0, it is crucial for organizations to be able to develop and adopt systems and business models that complement the implementation of CSC and Industry 4.0 business practices to boost environmental sustainability (Khan et al., 2017; Saucedo-Martínez et al., 2017; Luthra and Mangla, 2018; Mangla et al., 2018a).

2.11 Skilled and Semi-Skilled Employees

Implementation of Industry 4.0 requires a workforce to acquire new skills (Jabbour et al., 2018b). Implementation of CSC also requires highly scientific skills. Moreover, it takes a certain skill set to develop products that are appropriate for circular economy principle while supporting refurbishment, reuse and recycling etc. (Zhu and Geng, 2013; Jabbour et al., 2018b). Thus, for enhancing the sustainability in supply chain operations via integrating Industry 4.0 and CSC, organisations need to ensure that their employees at various levels possess the requisite skills.

2.12 Top Management Commitment

Transformations for attaining environmental sustainability are mainly driven by a committed approach towards sustainable development. To make it possible to implement CSC, management commitment is considered to be essential (Giunipero et al, 2012; Zhu and Geng, 2013; Venkatesh and Luthra, 2016; Mangla et al., 2018a). Moreover, top management carries the responsibility to proactively identify opportunities for the organization to integrate Industry 4.0 technologies in their circular supply chain (Jabbour et al, 2018b).

2.13 Management Leadership

Leadership style is likely to govern the adoption of emerging trends by organizations (Shao et al., 2017). Onar et al. (2018) highlighted the role of leadership in integrating practices that are concerned with sustainability. Effective leadership involves particular capabilities that are essential to success (Abell, 2006). For instance, a transformational leadership style facilitates integrated implementation of CSC and Industry 4.0 by inspiring followers to prioritize organizational interest over their personal gains. Jabbour et al. (2018) have also reiterated the crucial significance of management leadership for adoption of sustainable practices in organizations.

2.14 Financial Resources

We argue that organisations are in need of major investment to build the requisite capabilities for adoption of circular supply chain integrated with Industry 4.0. Therefore, we propose that access to financial resources of an organisation is critical to augment sustainability in supply chain operations via implementing the stated strategies. Luthra and Mangla (2018) reiterate the significance of financial resources for applying Industry 4.0 proposed by other studies (Theorin et al. 2017). Moreover, financial resources are also mentioned as critical for adoption of CE business models (Mangla et al., 2018a).

3. Research methodology

3.1. Methodology framework

The study is conducted into three phases as shown in Figure 1. In the first phase, an explorative approach is taken by utilising the literature studied and expert input to identify the CSFs that affect CSC. The output of this phase is presented in section 2. In the second phase, verification is carried out by seeking the opinions of experts regarding the CSFs. In phase 3, Hesitant Fuzzy DEMATEL is employed to find the inter-relationships among CSFs. The application and outputs of Phases 2 and 3 are presented in section 4. However, the individual steps of Phase 3 are presented in the next sub-section (sub-section 3.2).

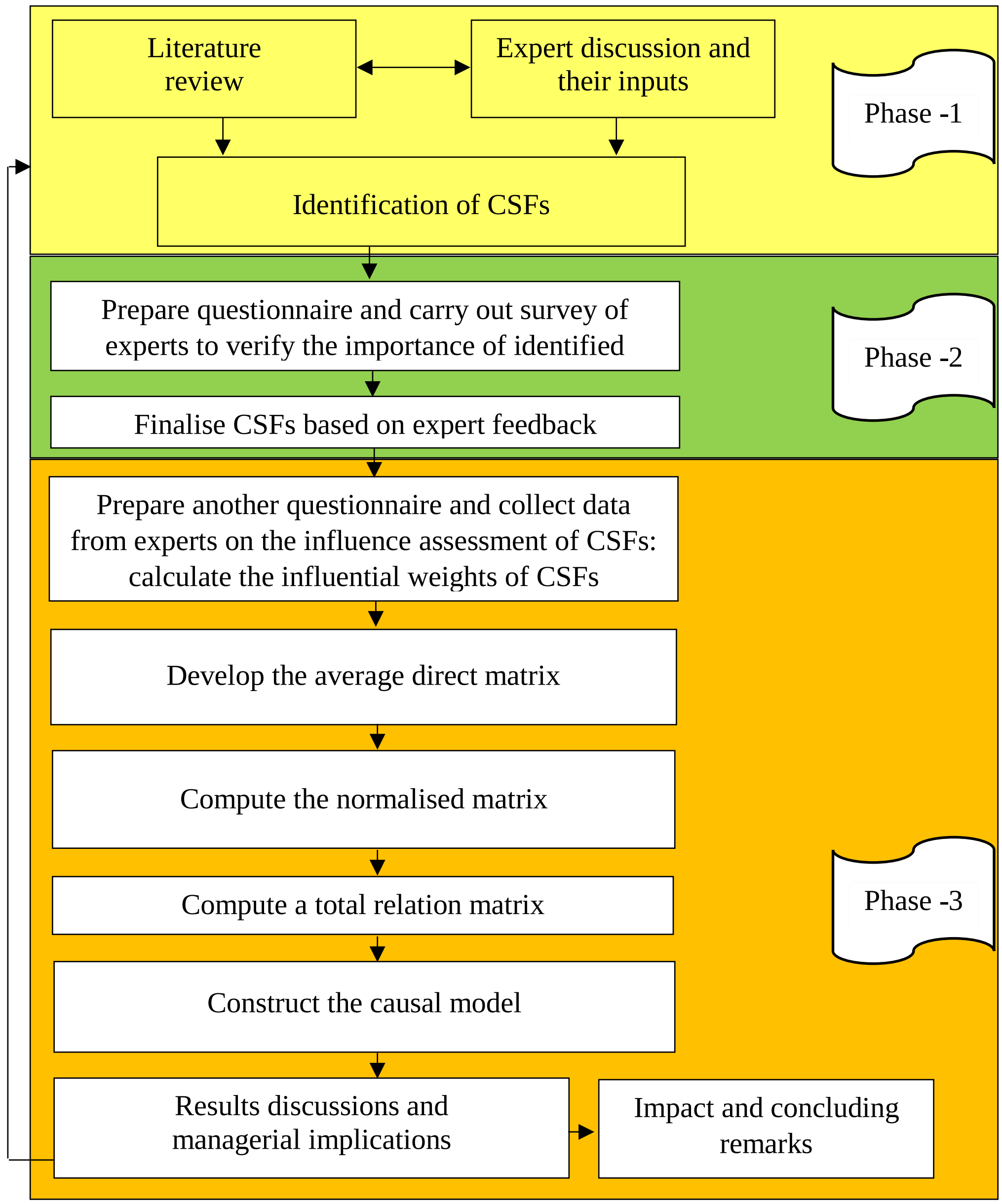

Figure 1. Methodology framework of the study

3.2. Hesitant Fuzzy DEMATEL (HF-DEMATEL)

The hesitant fuzzy sets provide the flexibility to manage the decision-makers' hesitancy over matters (Torra, 2010; Chen et al., 2013). The most important concepts related to HFSs are described as follows.

Given a fixed set $Y = \{y_1, y_2, \dots, y_n\}$, a HFS on Y is a subset of [0, 1] (Torra, 2010). As per Xia and Xu (2011), this can be presented in the following mathematical form;

$$M = \{\langle y, h(y)\rangle \mid y \in Y\}, \tag{1}$$

where $h(y)$ is a set of some values in [0, 1], $y \in Y$ to the set M. M stands for the set of total HFSs in Y (Xia and Xu, 2011). In this regard, M can be denoted by

$$M = \left\{\left\langle y, \bigcup_{\gamma \in h(x)} \{\gamma\}\right\rangle \mid y \in Y\right\},$$

The classical DEMATEL was proposed by the Battelle Memorial Institute in Geneva in 1971. This method has since been used extensively by researchers in many different fields to develop inter-dependence relationships among variables (Chen et al., 2013; Wu et al., 2017; Asan et al., 2018; Han et al., 2018). But this classical method is not able to capture the vagueness of the data set; an extension of this method was therefore explored with different theories to deal with uncertain situations (Büyüközkan et al., 2017; Luthra et al., 2018). But these extensions are not able to handle the hesitancy over objects. To overcome this issue, the hesitant fuzzy sets provide the flexibility to manage the decision-makers' hesitancy over matters (Torra, 2010; Chen et al., 2013). The involved mathematical steps of HF-DEMATEL are provided as follows:

Step 1. Collect experts' opinions to construct a hesitant fuzzy direct-influence matrix.

Step 2. Obtain the crisp direct-influence matrix

Step 3. Compute the normalized direct-influence matrix

Where, $B = k \times \bar{A}$

$$k = \min\left(\frac{1}{\max_i\left(\sum_{i=1}^{n} a_{ij}\right)}, \frac{1}{\max_j\left(\sum_{j=1}^{n} a_{ij}\right)}\right), i, j = 1, 2, ...n. \tag{2}$$

Step 4. Derive the total-influence matrix by

$$T = B(I - B)^{-1} \tag{3}$$

Total sum of rows and columns of the T matrix, are obtained from Eqs. (5-6) as below:

$$r = [r_i]_{n\times 1} = \left[\sum_{j=1}^{n} t_{ij}\right]_{n\times 1} \tag{4}$$

$$c = [c_i]_{1\times n} = \left[\sum_{i=1}^{n} t_{ij}\right]_{1\times n} \tag{5}$$

Where t_{ij} is total relation matrix, for $i, j = 1, 2, \ldots, n$.

Step 5. In order to construct a causal model and to avoid minor impact Eq. (6) is used.

$$\alpha = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}\left[t_{ij}\right]}{N} \tag{6}$$

where N signifies all elements. Those values greater than (α) are taken into account to construct the causal model.

4. Analysis

As per the research methodology framework as shown in Figure 1, this section provides details of how phases 2 and 3 were employed for verification and assessment of the influence of the CSFs.

4.1 Finalization of CSFs

Industry 4.0 and circular practices are emerging topics in the context of sustainability in supply chains. Thus, critical success factors play a significant role in the applicability of Industry 4.0 and circular practices in the supply chain of an organization to achieve long term sustainability. Therefore, to establish a comprehensive analysis for factors in the purview of organisations that guide the adoption of stated approaches, a literature review was initially carried out to identify the critical success factors that align Industry 4.0 and CSC; fourteen related factors were identified. To check their importance and applicability for practical purposes, it is important to take into account the opinion of experts about these factors. Thus, experts who are working in these areas were contacted. For this process, the phase 2 study steps of the research methodology framework as provided in Fig.1 are followed. Using the questionnaire in Appendix A, the experts from industry and academia were requested to give their opinions; data from twenty one experts was collected. Mean and standard deviation of all factors are calculated by using excel software as shown in Table 2. The mean score for each factor is greater than the accepted threshold value (i.e. 3.5) determined in relevant literature (Kumar et al., 2018a; Kapse et al., 2018). This shows the relevance and importance of the factors.

Table 2. Mean and standard deviation (SD) values of CSFs

Sl. No.	Name of factor	Mean	SD
F1	Coordination and collaboration among supply chain partners	4.100	.641
F2	Change management	4.000	.795
F3	Knowledge of circular supply chain and Industry 4.0	4.500	.607
F4	Training and development programs	3.700	.733

F5	High quality data	4.450	.605
F6	Effective planning and execution	3.650	1.039
F7	Integration of technology platforms	4.150	.671
F8	Data security	4.500	.607
F9	Knowledge management system	3.950	.945
F10	Ability to adopt new business models	4.150	.813
F11	Skilled and semi-skilled employees	4.350	.745
F12	Top management commitment	3.750	.910
F13	Management leadership	3.800	.951
F14	Financial resources	4.250	.786

4.2. Evaluation of CSFs using Hesitant Fuzzy DEMATEL

As per the framework in Fig.1, a step by step evaluation of identified CSFs for integration of industry 4.0 and circular practices towards sustainability in SC for an organizational level is provided in this sub-section as follows.

Step1. Influencing assessment of CSFs by using Hesitant Fuzzy DEMATEL. Based on the pre-designed questionnaire as shown in Appendix B, experts from the automobile industry were contacted for data collection. The Indian government aspires to achieve a target of increasing the contribution of manufacturing output to 25% of country's GDP by 2025 from the current level of 16% (IBEF, 2018). The automobile industry in India has grown remarkably at a CAGR of 6% during FY 2006-16 (IBEF, 2018). Currently, India is one of the largest manufacturers globally of two-wheeler vehicles, three-wheeler vehicles and tractors. The Indian automotive industry is also among the early adopters of Industry 4.0 (AIMA-KPMG, 2018). Therefore, we conducted this study in the context of the Indian automotive industry in the hope that these findings will help all managers in effective adoption of Industry 4.0. Data has been collected from Indian automotive industry experts. All selected experts have more than fifteen years' experience in the automobile industry and their respective areas; they are well aware of the concept of industry 4.0 and circular economy issues. Moreover, organisations of the selected experts are actively involved in taking initiatives to become environmentally sustainable. To select experts, we used convenience and snowball sampling - non-probability sampling methods. After contacting one expert, that expert referred the research team to another expert working in the same area and with vast experience in our research topic. Group size can affect the result but an over large decision-making group is also not recommended; it should be roughly 5-50 (Gumus, 2009). After following this process, we were able to collect our data from five experts; this number of experts in a group is quite acceptable, as seen in previous studies (Kumar et al., 2018b; Kusi-Sarpong et al., 2019). The influence assessments of all selected experts on critical successful factor (F1) is given in Table 3; the same step was followed for all other factors for collective hesitant fuzzy direct-influence matrix A containing the judgements of all decision makers.

Step2. Crisp direct-relationship matrix for CSFs. The crisp direct-influence matrix is determined as shown in Table 4.

Step3. Compute the normalised matrix. By using Equation (2), the normalization matrix is computed as shown in Table 5.

Step 4. Compute the total relation matrix. With the help of Equation (3), the total relation matrix was computed and presented in Table 6. The sum of rows and columns i.e (r_i+c_j) and (r_i-c_j) is totalled by Equations (4) and (5) using excel software as depicted in Table 7. A factor is considered in the cause group if it contains a positive value of (r_i-c_j); otherwise it is included in the effect group.

Step 5. Construct the causal model. To draw a relationship digraph of the CSFs for CSFs, Equation (7) is utilized to establish a threshold value (α) of 0.826. Those values that are > 0.826 are used to construct the relationship digraph of the CSFs. For clarity, red text is used for these values in Table 6. For instance, the value of t_{12} (0.852) > α (0.826); this presents the significance or strength of relationship and is shown in the digraph with an arrow; for instance, F1 to F2 means F1 affects F2. The same steps were followed for others factors and the graphical cause-effect representation of CSFs through a digraph is presented in Figure 2.

Table 3. Influence assessment of experts on F1

	F1					
CSFs	1	2	3	4	5	Collective opinion
F2	0.5	0.4	0.6	0.5	0.3	{0.5, 0.4, 0.6, 0.3}
F3	0.6	0.6	0.7	0.7	0.5	{0.6, 0.7, 0.5}
F4	0.6	0.4	0.7	0.8	0.5	{0.6, 0.4, 0.7, 0.8, 0.5}
F5	0.5	0.5	0.6	0.9	0.4	{0.5, 0.6, 0.9, 0.4}
F6	0.7	0.6	0.6	0.5	0.8	{0.7, 0.6, 0.5, 0.8}
F7	0.4	0.3	0.6	0.7	0.8	{0.4, 0.3, 0.6, 0.7, 0.8}
F8	0.5	0.5	0.6	0.6	0.5	{0.5, 0.6, 0.7}
F9	0.6	0.4	0.7	0.5	0.8	{0.6, 0.4, 0.7, 0.5, 0.8}
F10	0.7	0.5	0.8	0.6	0.7	{0.7, 0.5, 0.8, 0.6, 0.7}
F11	0.8	0.7	0.6	0.5	0.6	{0.8,0.7, 0.6, 0.5}
F12	0.6	0.6	0.7	0.8	0.9	{0.6,0.7, 0.8, 0.9}
F13	0.5	0.7	0.6	0.6	0.4	{0.5, 0.7, 0.6, 0.4}
F14	0.6	0.4	0.5	0.5	0.8	{0.6, 0.4, 0.5, 0.8}

Table 4. Crisp direct-relationship matrix for CSFs

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14
F1	0.000	0.550	0.600	0.550	0.580	0.600	0.500	0.550	0.575	0.600	0.550	0.575	0.600	0.575
F2	0.450	0.000	0.550	0.620	0.550	0.566	0.650	0.600	0.500	0.600	0.550	0.500	0.500	0.650
F3	0.600	0.475	0.000	0.600	0.533	0.650	0.600	0.600	0.550	0.500	0.520	0.680	0.550	0.560
F4	0.600	0.650	0.520	0.000	0.700	0.550	0.660	0.425	0.675	0.500	0.500	0.500	0.500	0.580
F5	0.680	0.550	0.675	0.625	0.000	0.600	0.566	0.500	0.480	0.600	0.600	0.550	0.560	0.450
F6	0.600	0.650	0.475	0.550	0.633	0.000	0.575	0.500	0.500	0.525	0.525	0.520	0.550	0.500
F7	0.560	0.525	0.600	0.633	0.525	0.550	0.000	0.550	0.475	0.450	0.550	0.550	0.500	0.525
F8	0.600	0.600	0.525	0.550	0.500	0.500	0.500	0.000	0.550	0.575	0.633	0.500	0.550	0.650
F9	0.625	0.575	0.500	0.550	0.475	0.500	0.550	0.650	0.000	0.675	0.450	0.475	0.550	0.725
F10	0.663	0.550	0.500	0.450	0.525	0.633	0.575	0.550	0.550	0.000	0.500	0.650	0.450	0.650
F11	0.650	0.650	0.566	0.625	0.575	0.550	0.533	0.475	0.600	0.450	0.000	0.525	0.550	0.500
F12	0.750	0.575	0.475	0.575	0.575	0.700	0.550	0.550	0.600	0.633	0.575	0.000	0.475	0.400
F13	0.550	0.575	0.525	0.525	0.625	0.500	0.600	0.625	0.540	0.550	0.500	0.475	0.000	0.525
F14	0.575	0.450	0.550	0.575	0.550	0.525	0.550	0.600	0.500	0.550	0.600	0.625	0.600	0.000

Table 5. Normalization matrix for CSFs

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14
F1	0.000	0.070	0.076	0.070	0.073	0.076	0.063	0.070	0.073	0.076	0.070	0.073	0.076	0.073
F2	0.057	0.000	0.070	0.078	0.070	0.072	0.082	0.076	0.063	0.076	0.070	0.063	0.063	0.082
F3	0.076	0.060	0.000	0.076	0.067	0.082	0.076	0.076	0.070	0.063	0.066	0.086	0.070	0.071
F4	0.076	0.082	0.066	0.000	0.089	0.070	0.084	0.054	0.085	0.063	0.063	0.063	0.063	0.073
F5	0.086	0.070	0.085	0.079	0.000	0.076	0.072	0.063	0.061	0.076	0.076	0.070	0.071	0.057
F6	0.076	0.082	0.060	0.070	0.080	0.000	0.073	0.063	0.063	0.066	0.066	0.066	0.070	0.063
F7	0.071	0.066	0.076	0.080	0.066	0.070	0.000	0.070	0.060	0.057	0.070	0.070	0.063	0.066
F8	0.076	0.076	0.066	0.070	0.063	0.063	0.063	0.000	0.070	0.073	0.080	0.063	0.070	0.082
F9	0.079	0.073	0.063	0.070	0.060	0.063	0.070	0.082	0.000	0.085	0.057	0.060	0.070	0.092
F10	0.084	0.070	0.063	0.057	0.066	0.080	0.073	0.070	0.070	0.000	0.063	0.082	0.057	0.082
F11	0.082	0.082	0.072	0.079	0.073	0.070	0.067	0.060	0.076	0.057	0.000	0.066	0.070	0.063
F12	0.095	0.073	0.060	0.073	0.073	0.089	0.070	0.070	0.076	0.080	0.073	0.000	0.060	0.051
F13	0.070	0.073	0.066	0.066	0.079	0.063	0.076	0.079	0.068	0.070	0.063	0.060	0.000	0.066
F14	0.073	0.057	0.070	0.073	0.070	0.066	0.070	0.076	0.063	0.070	0.076	0.079	0.076	0.000

Table 6. Total direct relation matrix for CSFs

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14
F1	0.839	0.852	0.827	0.858	0.853	0.863	0.850	0.832	0.827	0.842	0.821	0.831	0.814	0.847
F2	0.880	0.775	0.810	0.853	0.838	0.847	0.854	0.825	0.807	0.829	0.809	0.810	0.792	0.843
F3	0.911	0.845	0.758	0.865	0.850	0.870	0.862	0.838	0.826	0.832	0.819	0.843	0.810	0.846
F4	0.905	0.859	0.815	0.789	0.862	0.853	0.863	0.814	0.834	0.826	0.811	0.818	0.799	0.843
F5	0.922	0.856	0.839	0.870	0.789	0.867	0.861	0.829	0.820	0.844	0.829	0.831	0.813	0.836
F6	0.878	0.833	0.785	0.828	0.829	0.762	0.828	0.797	0.790	0.804	0.789	0.795	0.780	0.809
F7	0.862	0.809	0.788	0.826	0.807	0.817	0.750	0.792	0.777	0.785	0.781	0.788	0.765	0.801
F8	0.891	0.841	0.803	0.841	0.827	0.835	0.833	0.750	0.808	0.822	0.813	0.806	0.793	0.838
F9	0.901	0.844	0.806	0.847	0.831	0.841	0.845	0.833	0.749	0.839	0.799	0.809	0.799	0.853
F10	0.900	0.836	0.801	0.831	0.831	0.851	0.842	0.816	0.809	0.756	0.800	0.824	0.783	0.839
F11	0.899	0.848	0.809	0.851	0.838	0.842	0.839	0.809	0.815	0.810	0.741	0.810	0.795	0.824
F12	0.930	0.859	0.816	0.863	0.856	0.877	0.858	0.834	0.833	0.848	0.826	0.765	0.803	0.830
F13	0.873	0.826	0.791	0.826	0.829	0.823	0.832	0.812	0.795	0.807	0.787	0.791	0.716	0.813
F14	0.891	0.826	0.807	0.845	0.835	0.839	0.840	0.822	0.804	0.821	0.811	0.821	0.800	0.763

Note: those values greater than threshold value (i.e. 0.826) are marked with red and used for developing cause-effect digraph as shown in Figure 2.

Table 7. Cause/effect parameters for CSFs

CSFs	r_i	c_j	r_i+c_j	$r_i- c_j$	Group	CSFs	r_i	c_j	r_i+c_j	$r_i- c_j$	Group
F1	11.757	12.483	24.240	-0.725	Effect	F8	11.501	11.403	22.903	0.098	Cause
F2	11.571	11.710	23.281	-0.140	Effect	F9	11.595	11.293	22.888	0.302	Cause
F3	11.774	11.255	23.029	0.519	Cause	F10	11.520	11.464	22.984	0.056	Cause
F4	11.690	11.791	23.481	-0.101	Effect	F11	11.530	11.237	22.766	0.293	Cause
F5	11.806	11.675	23.481	0.131	Cause	F12	11.799	11.342	23.141	0.457	Cause
F6	11.307	11.787	23.094	-0.480	Effect	F13	11.322	11.062	22.384	0.260	Cause
F7	11.147	11.758	22.905	-0.611	Effect	F14	11.526	11.585	23.111	-0.058	Effect

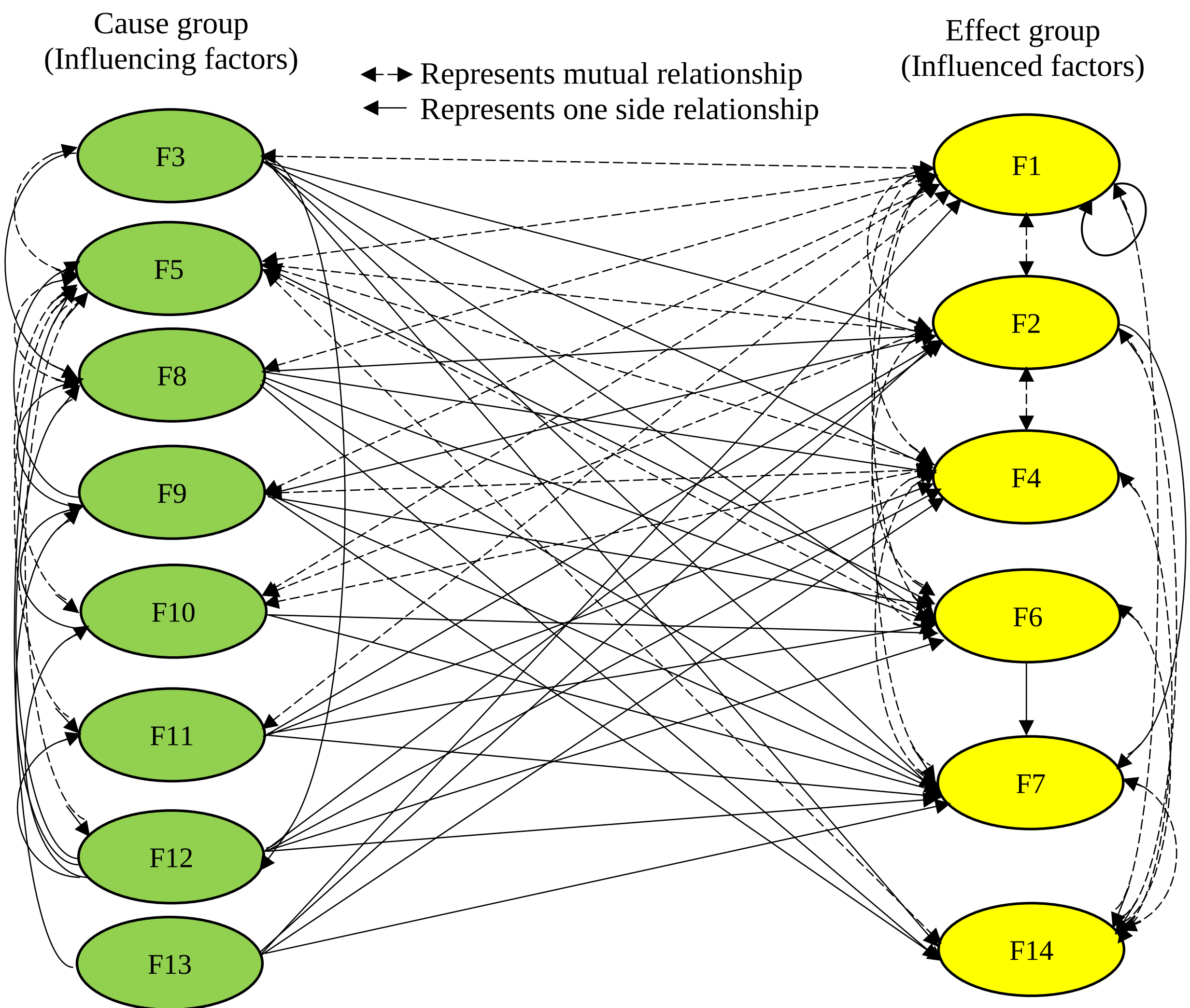

Figure 2. Relationship digraph of CSFs

5. Discussion of finding

The main output of the HF-D analysis is the division of the CSFs into cause and effect groups as shown in Table 5. Out of fourteen factors, six factors, namely, F1, F2, F4, F6, F7 and F14 are in the effect (influenced) group and eight factors, namely, F3, F5, F8, F9, F10, F11, F12, and F13 are in the cause (influencing) group. A detailed discussion is given below.

5.1 Cause (influencing) group factors

All cause group factors are influencing factors as they exert influence on other factors. Therefore, these critical factors play a major role in adoption of CSC integrated with Industry 4.0 to achieve sustainability in SC operations. A comprehensive understanding of these factors will help organizations to formulate plans of action to achieve the stated objective.

"Knowledge of circular supply chain and Industry 4.0" (F3) has the highest (r - c) value of 0.519 (as shown in Table 5), emerging as the most crucial factor in the cause group. This particular factor is not only crucial in itself to accomplish the stated objective, but also influences organisational capability to enable Industry 4.0 driven circular supply chain implementation by influencing other critical success factors, as demonstrated in Figure 2. Therefore, it is important for organisations to make efforts, such as conducting regular awareness and training programs, to maximise knowledge of Industry 4.0 and circular SC (Batista et al., 2018; Luthra and Mangla, 2018). Providing open discussion forums to facilitate innovation by employees and motivating them to participate is crucial; this will raise awareness and enhance skills needed to achieve sustainability through integrating circular SC and Industry 4.0. With a (r - c) value of 0.457, "top management commitment" (F12) is the second most crucial factor in the cause group. As described in Figure 2, this factor influences eleven others under consideration as critical success factors. This factor has emerged as highly significant due to the fact that "top management commitment" towards implementing Industry 4.0 integrated circular supply chain forms the basis to build other requisite organisational capabilities needed in this context. Hence, strong commitment from management is essential for effective execution of the desired integration (Jabbour et al., 2018a, b; Kamble et al., 2018a; Luthra and Mangla, 2018). "Knowledge management system" (F9) is the third most important factor in the cause group category, with a (r - c) value of 0.302; this exerts an influence on nine other critical success factors (as demonstrated in Figure 2). Knowledge management system (F9) has a bi-directional relationship with change management (F2) and training and development programs (F4). This finding indicates the importance of a knowledge management system in an organization. These findings highlight the significance of an efficient knowledge management system for organizations to adopt circular supply chain integrated with Industry 4.0 (Kache and Seuring, 2017; Luthra and Mangla, 2018; Hislop et al., 2018). "Skilled and semi-skilled employees" (F11) is the next most important cause group factor with (r – c) value of 0.293. The cause-effect relation map (Figure 2), indicates the existence of six influencing relationships in these factors, among which two are bi-directional - namely F1 and F5. These findings show that having qualified employees is proven to give a competitive edge for organizations to be able to take steps towards accomplishing their goals. "Management leadership"

(F13) comes in fifth position with a (r-c) score of 0.293; five other critical success factors are influenced by the dynamics of this factor. These findings reiterate that leadership style is a key factor of influence in the performance of employees (Gill and Caza, 2018). With (r – c) scores of 0.131, 0.098 and 0.056, "high quality data" (F5), "data security" (F8) and "ability to adopt new business models" (F10) take sixth, seventh and eighth positions in the cause group.

5.2 Effect (Influenced) group factors

These factors are the factors that are influenced by others factors. These factors play a significant role in identifying and analysing the reflection of cause group factors. This information is likely to help managers in effective planning to accomplish the desired objective with minimum cost. Out of the fourteen CFs under consideration, six factors namely, coordination and collaboration among supply chain partners (F1); change management (F2); training and development programs (F4); effective planning and execution (F6); integration of technology platforms (F7) and financial resources (F14) fall into the effect group. Coordination and collaboration among supply chain partners and integration of technology platforms with (r – c) scores of -0.725 and -0.611 are ranked in first and second positions respectively. Hence, these factors are crucial for organisations to be able to boost sustainability of their operations via adopting circular supply chain integrated with Industry 4.0. Therefore, decision makers and practitioners must strategize efforts to maintain a well-coordinated and collaborative association with their supply chain partners. A systematic integration of technology platforms factor is also a very important organisational capability in this context. As per the (r – c) scores, effective planning and execution, change management, training and development and financial resources claim third, fourth, fifth and sixth positions in the effect group.

5.3 Research implications

5.3.1 Practical implications

The cause-effect framework among the CSFs can inform practitioners and decision makers in the automotive industry in having a better understanding of influencing and influenced factors. This understanding is likely to turn into optimised decision making for boosting sustainability of organisational operations in the automotive sector via integrating CSC and Industry 4.0. In addition, managers in the automotive industry who are looking to minimise environment footprints and deal with resource scarcity, are offered a number of practical implications as mentioned below:

- It is in the interest of the entire eco-system to protect the environment and minimise use of scarce resources for future generations. Therefore, governments should also support organisations to build the necessary capabilities to adopt sustainable practices. Skilled employees and a knowledge of CSC and Industry 4.0 are both cause group variables. Governments can help organisations in optimising these factors by running training programs to upgrade and disseminate requisite skills among the workforce. It is vital to raise awareness and knowledge relating to environmental sustainability, Industry 4.0 and a circular economy.
- The findings of this current work are likely to contribute to the understanding of practitioners and decision makers to define the key factors that define successful adoption of circular supply chain integrated with Industry 4.0.
- Results of the present study also contribute towards developing an understanding of the resulting impact of specific factors over other critical factors under consideration for the purpose of prioritisation and more efficient decision-making.
- By taking the key causal factors, such as knowledge management, into account, system organisations can improve their strategies regarding knowledge creation and knowledge sharing. An understanding of these factors is also significant during recruitment as it may guide organisations to hire the most suitable individuals. In a nutshell, knowledge of causal factors is likely to transmit into formulation of appropriate strategies which in turn will guide companies towards successful practice.

5.3.2 Theoretical implications

The theoretical contributions are given as follows:

- The current work identifies and validates fourteen critical success factors for an organisation for enhancing sustainability in supply chain operations via implementation of Industry 4.0 integrated CSC. This has been attained through a comprehensive review of current literature combined with expert consultations.
- Hesitant fuzzy DEMATEL based method has been developed that analyses the critical factors and provides a deep understanding of the causal relationships amongst the critical success factors.

6. Concluding remarks

Circular supply chain is becoming increasingly crucial due to the rapid depletion of natural resources and growing worries about climate change. Industry 4.0 technologies can play a significant role in moving towards implementing circular economy principles in supply chain in various ways, such as by enabling tracking of products post-consumption so that components can be recovered. Moreover, Industry 4.0 also contributes towards environmental protection and attaining resource efficiency. But, integrating Industry 4.0 with circular supply chain is likely to create synergy in addressing the issues of climate change and resource scarcity. Therefore, the current work attempts to support organisations in successful adoption of Industry 4.0 integrated circular supply chain to ultimately augment the sustainability of their supply chain operations. Conceptually, the present study identifies fourteen CSFs in the purview of organisations that govern their ability to adopt Industry 4.0 integrated circular SC. A combined approach of detailed review of literature and expert validation was taken to obtain these CSFs. A hesitant based fuzzy DEMATEL method was developed and implemented, analysing these CSFs to build the cause-effect relationships among them. Findings of the current work specify eight factors - F3, F5, F8, F9, F10, F11, F12 and F13 - that form a cause group; the remaining six factors - F1, F2, F4, F6, F7 and F14 – form the effect group. Fundamentally, cause group factors are 'input' variables that influence the success of the desired outcome. Cause group variables also influence the dynamics of the effect group factors as well. Therefore, the cause group bears more applicability for decision makers due to the fact that correction in cause group factors also transmits to the effect group factors. Knowledge about circular SC and Industry 4.0 (F3) emerged as the most critical factor in the cause group, followed by top management commitment (F12), knowledge management system (F9), skilled and semi-skilled employees (F11), management leadership (F13), high quality data (F5), data security (F8) and ability to adopt new business models (F10). This order of significance of CSFs is of key importance for practitioners and decision makers for prioritisation purposes. Coordination and collaboration among supply chain partners (F1) stands out to be the most influential factor among other effect group factors. Integration of technology platforms (F7) is ranked as the second most important effect group factor followed by effective planning and execution (F6), change management (F2), training and development (F4) followed by financial resources (F14). The discussion of practical and theoretical implications completes the examination of all identified research questions.

6.1 Limitations and future research directions

This work has a few limitations that can form the basis of conducting future research in this area. Any future studies can extend the scope of identifying the critical successful factors at macro level as the current work takes into account only those factors that are relevant at organisational level. To validate the cause-effect relationships, an empirical study can be conducted in future. This study is based on the Indian automotive industry; future research can be conducted in different industry perspectives. In this study, we used a Hesitant fuzzy DEMATEL technique to establish the inter-relationships among identified critical success factors; further examination of these inter-relationships in future research can be developed and hypotheses that arise can be tested empirically.

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Appendix A

Phase 1 - Finalization of critical success factors (in the purview of organisations) for implementing Industry 4.0 integrated circular supply chain to augment sustainability in supply chain operations

Greetings!!!!

Dear respondent, current research attempts to evaluate the key capabilities of an organisation for implementing Industry 4.0 integrated circular supply chain to augment sustainability in its supply chain operations. We have identified 14 critical success factors from current literature. Kindly provide your responses about the relevance of the following literature based critical success factors for organisations that are willing to implement Industry 4.0 integrated circular supply chain. You are also free to merge/delete/rephrase/ the critical success factors which you think are relevant in the given context. Please respond based on the scale 5 – very important to 1 – not at all important.

Critical Success Factors for implementing Industry 4.0 integrated circular supply chain	**Response**
Coordination and collaboration among supply chain partners	
Change management	
Knowledge of circular supply chain and Industry 4.0	
Training and development programs	
High quality data	
Effective planning and execution	
Integration of technology platforms	
Data security	
Knowledge management system	
Ability to adopt new business models	
Skilled and semi-skilled employees	
Top management commitment	
Management leadership	
Financial resources	
If any others, please add….	

Appendix B

Phase 2 - Influencing assessment factors of integration of Industry 4.0 and circular practices towards sustainability in supply chain: An organizational micro perspective

Please rate the influencing assessment of one CSF to another based on the following scale: 0.0 - Absolutely low influence 0.1 - Low influence 0.2 - Fairly low influence 0.3 - Medium influence 0.4 - Fairly medium low influence 0.5 - High influence 0.6 - Fairly high influence 0.7 - High influence 0.8 - Absolutely high influence 0.9 - Very high influence	**Compare the influence of one critical factor over another as per mentioned scale**													
	Coordination and collaboration among supply chain partners	Change management	Knowledge of circular supply chain and Industry 4.0	Training and development programs	High quality data	Effective planning and execution	Integration of technology platforms	Data security	Knowledge management system execution	Ability to adopt new business models	Skilled and semi-skilled employees	Top management commitment	Management leadership	Financial resources
Coordination and collaboration among supply chain partners	0													
Change management		0												
Knowledge of circular supply chain and Industry 4.0			0											
Training and development programs				0										
High quality data					0									
Effective planning and execution						0								
Integration of technology platforms							0							
Data security								0						
Knowledge management system									0					
Ability to adopt new business models										0				
Skilled and semi-skilled employees											0			
Top management commitment												0		
Management leadership													0	
Financial resources														0